

## Near Infrared Reflectivity of Venus and Ice Clouds

JAMES E. HANSEN AND HOWARD CHEYNEY

*Institute for Space Studies, Goddard Space Flight Center, NASA, New York, N. Y.*

(Manuscript received 15 April 1968)

### ABSTRACT

The near infrared reflectivity of ice clouds is computed and compared to observations of Venus. The difficulty in making an exact correction for CO<sub>2</sub> absorption precludes the possibility of either establishing or absolutely ruling out ice particles as the primary cloud constituent; however, it is possible to conclude that the clouds are not optically thick and composed of large ice crystals. There is still disagreement as to the quantitative significance of the infrared spectra, but, if it is assumed that a 20% depression may exist in the continuum near 2.0  $\mu$ , then optically thin clouds ( $\tau \leq 5-10$ ) of ice particles with radii  $\leq 4 \mu$  are compatible with the observations. It is shown that there is a small amount of positive evidence for such clouds.

### 1. Introduction

Although the recent observational and theoretical investigations of Venus have greatly expanded our knowledge of that planet's atmosphere, the composition of the cloud particles is still unknown. Until a space probe samples the particles themselves, our primary source of information on them will probably continue to be the solar light reflected by Venus and observed on earth. The absolute value and the wavelength dependence of the absorptivity of most materials is such that the near infrared is the most likely wavelength region for the reflectivity of the clouds to show measurable variations which can be correlated to particle composition. The interpretation, however, is complicated by the strong absorption shown by many gases in the same region. Even if the exact composition of the atmosphere of Venus were known it would be difficult to make a valid correction for gaseous absorption because, first, there is not a practical method for solving the transfer problem with highly anisotropic scattering and wavelength-dependent absorption and, second, there is not sufficient evidence on the physical structure of the clouds. However, it is worthwhile to examine the spectra for the presence of gross features expected for ice clouds and to compare the magnitude of those features, or upper limits on them, to theoretical calculations for the reflectivity of ice clouds.

### 2. Observations

Bottema *et al.* (1964, 1965) obtained a reflection spectrum from 1.7–3.4  $\mu$  with a balloonborne telescope at a resolving power of 0.08  $\mu$ . They used the reflecting layer model to correct for assumed H<sub>2</sub>O and CO<sub>2</sub> absorption above the clouds of Venus and they made laboratory observations of the reflectivities of many possible cloud particle constituents. On the basis of a remarkable agreement between the spectral reflectivity of Venus

and the laboratory ice cloud (Fig. 1), they concluded that the clouds of Venus were ice. Sagan and Pollack (1967) then made calculations with a two-stream approximation which confirmed the identification, and they derived a cloud thickness  $18 \leq \tau \leq 43$  and a mean particle radius  $7.5 \mu \leq \bar{r} \leq 10.0 \mu$ .

However, higher resolution spectra obtained from the ground by Kuiper (1962) show no clear evidence of ice and Rea and O'Leary (1968) argue that the reflectivity minima at 1.5 and 2.0  $\mu$  are due almost entirely to CO<sub>2</sub> absorption. Rea and O'Leary convolved Kuiper's spectrum to degrade the resolution to that of Bottema *et al.* and the close fit that they obtained to the observed curve of Bottema *et al.* supports their argument. Recent observations by Kuiper<sup>1</sup> from a high altitude aircraft confirm his earlier results.

Thus, although the very low reflectivity observed by Bottema *et al.* near 3  $\mu$  is almost certainly due to absorption within the cloud particles themselves, the feature at 2  $\mu$  is, at least in large part, the result of CO<sub>2</sub> absorption. It is therefore impossible to derive unique cloud parameters from the observations, yet it is of interest to examine the question of whether or not it is possible for ice clouds to be compatible with the observations of both Bottema *et al.* and Kuiper, i.e.: Are there physically realistic ice clouds with a low reflectivity from 3.0–3.4  $\mu$  and yet with no reflectivity minima at 1.5 and 2.0  $\mu$  deep enough to be observed by Kuiper?

Rea and O'Leary (1968) examined the above question semiquantitatively and concluded that micron-sized particles were incompatible with the observations and that, if the particles were small enough to yield acceptably shallow minima at 1.5 and 2.0  $\mu$ , the reflectivity at 3.2–3.4  $\mu$  would be much too high. They argued that even if some additional material were present and absorbing at 3.2–3.4  $\mu$ , the ice particle diameters would

<sup>1</sup> Kuiper, G. P., 1968: Paper presented at the Second Arizona Conference on Planetary Atmospheres, Tucson, 11–13 March.

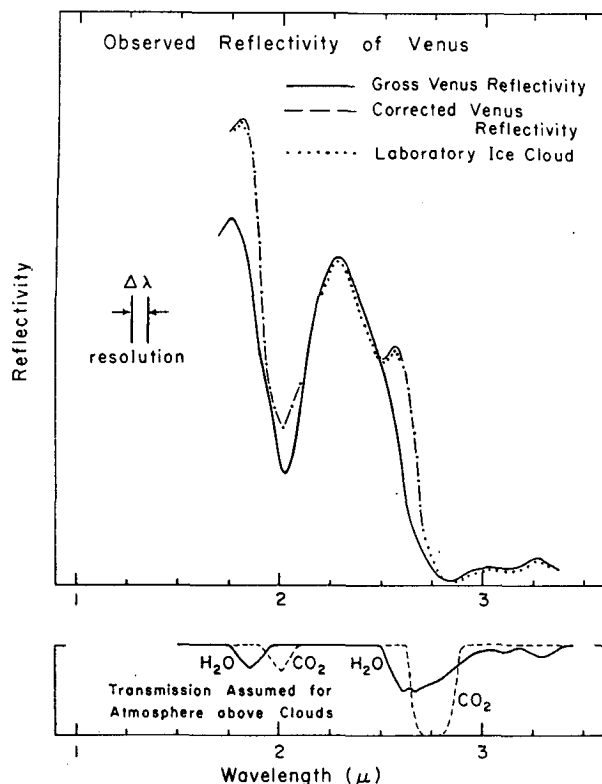


FIG. 1. Infrared reflectivity of Venus measured by Bottema *et al.* (1965) with a resolution  $0.08 \mu$ . The corrected Venus reflectivity was assumed by Bottema *et al.* to be the reflectivity of the cloud layer. This reflectivity was obtained by using a reflecting layer model and the transmissions shown in the lower part of the figure to correct for gaseous absorption.

have to be much less than  $1 \mu$ , and probably less than  $0.1 \mu$ , in order to be consistent with the  $1.5$  and  $2.0 \mu$  observations; therefore, since the existence of the required abundance of such particles on a planetwide basis is improbable, they concluded that the major scatterers of radiation are almost certainly not composed of ice.

In order to consider these questions in more quantitative detail the observations must be examined, so that in effect, error bars can be placed on the measured reflectivities. Bottema *et al.* reported a nearly constant reflectivity of  $\sim 5\%$  from  $3.0$ – $3.4 \mu$  but clearly the significance of the reported curve decreases with wavelength in that region. The indium arsenide detectors of Bottema *et al.* had a detectivity which increased with wavelength up to  $\sim 3.25 \mu$  and then decreased precipitously to practically zero at  $3.4 \mu$  (Strong *et al.*, 1966). Since the solar spectrum is decreasing in that region, the net result was that their response to the solar spectrum was approximately constant from  $\lambda \sim 1.8 \mu$  to  $\lambda \sim 3.25 \mu$  and then decreased sharply. An additional possible source of error above  $3 \mu$ , which also increased with wavelength, was the thermal emission from the blade of the beam chopper, although a correction was made for that. According to W. Plummer (private communica-

tion), the observed reflectivity was getting down into the noise level at  $3.3 \mu$ , and at  $3.4 \mu$  it was completely submerged, so that at the latter wavelength it is only possible to say that Venus is not highly reflective. Hence, it appears that ice clouds will not be inconsistent with the observations of Bottema *et al.* if they yield a reflectivity  $\lesssim 10\%$  at  $3.3 \mu$  and a reflectivity  $\lesssim 20\%$  at  $3.4 \mu$ .

The other observational question which must be examined is how deep the reflectivity minima at  $1.5$  and  $2.0 \mu$  could be without being detected by Kuiper. Pollack and Sagan (1968) argue that depressions of  $20\%$  are possible because the ratios of the reflectivities at two wavelengths separated by  $\sim 0.1$ – $0.4 \mu$  sometime differ that much between different observers as well as for the same observer at different times. Kuiper (*loc. cit.*), however, attributes at least part of the reflectivity variations to real changes in the atmospheric conditions on Venus and he states that the maximum depressions at  $1.5$  and  $2.0 \mu$  compatible with his observations are  $\sim 1\%$ . Rather than attempting to place weights on the values suggested by the opposing camps, we will consider individually the limit favored by Pollack and Sagan and that favored by Kuiper.

### 3. Numerical computations

Theoretical computations of the spectral reflectivity of ice clouds in the near infrared have been made to determine the magnitude of the expected ice absorption features and to determine their dependence on the particle size and on the cloud optical thickness. The single scattering phase functions and albedos were computed from Mie theory by H. Cheyney. The remaining computations and the application to Venus are the responsibility of J. Hansen.

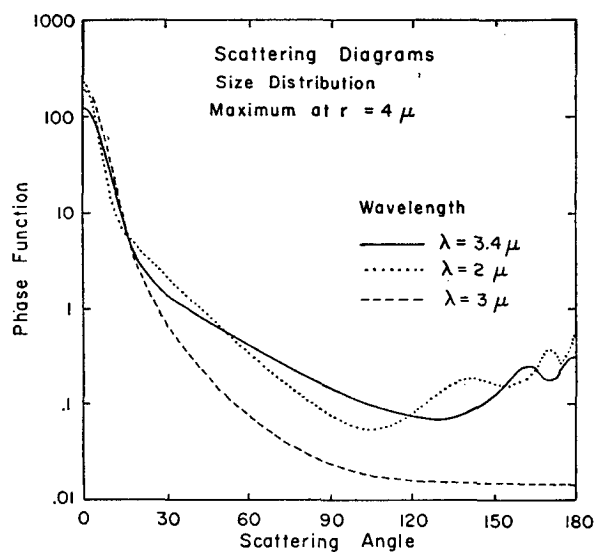


FIG. 2. Phase functions for three representative wavelengths in the near infrared. The phase functions are for spherical ice particles following the "cloud" model size distribution with the maximum of the distribution at a radius of  $4 \mu$ .

It has been shown elsewhere (Hansen and Cheyney, 1968) that the major features in laboratory reflectivity spectra of clouds of highly nonspherical but randomly oriented ice crystals may be matched theoretically by treating the particles as spheres of equivalent volume. The assumption of random orientation for the cloud particles on Venus is probably valid unless the particles are large and the atmosphere has little motion, but such conditions appear to be improbable. Therefore, computations were made for spherical ice particles with the "cloud" model size distribution used originally by Deirmendjian (1964). The upper limit of the size distribution was taken at a diameter of  $30\ \mu$  and the optical constants for ice were taken from the data compiled by Irvine and Pollack (1968). Some typical phase functions for one of the size distributions are shown in Fig. 2. These illustrate the strong forward scattering and the damping of backscattering at wavelengths where the absorption is large. The multiple scattering computations were made with a "double only" method described by Hansen (1968) which is based on a doubling principle first stated by van de Hulst (1963). In the method employed here the scattering and transmission functions for a layer of optical thickness  $\tau = 2^{-25}$  were obtained analytically from the phase function, since multiple scattering is negligible for a layer of that thickness. The

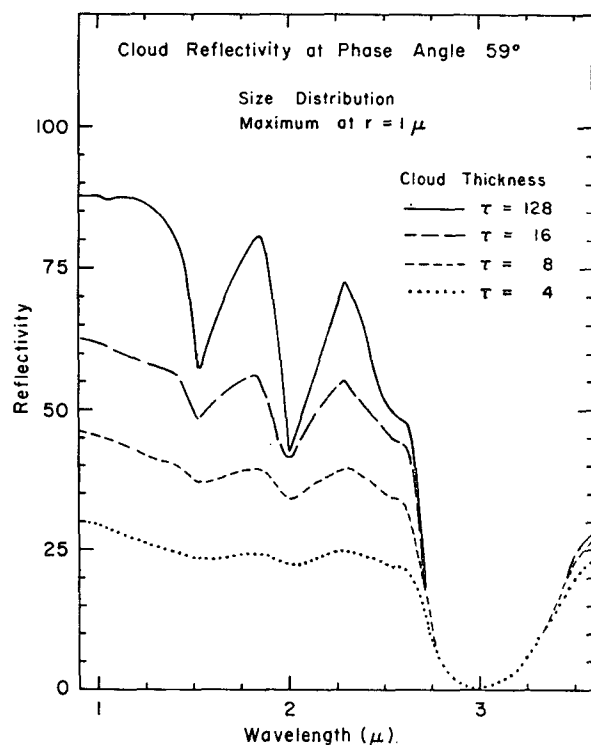


FIG. 3. Reflectivity of ice clouds in the near infrared. This is the intrinsic reflectivity of the clouds with no account taken of gaseous absorption or scattering by other particles. The calculations apply to Venus at the phase angle  $59^\circ$  and are for the "cloud" model size distribution with the maximum of the distribution at a radius of  $1\ \mu$ .

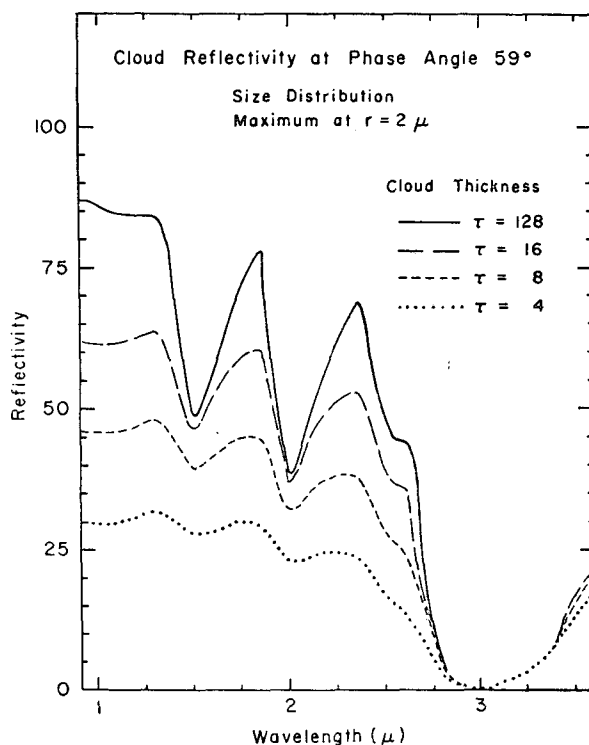


FIG. 4. Same as Fig. 3 except the size distribution has its maximum at  $2\ \mu$ .

corresponding functions for a plane parallel atmosphere of twice that thickness were then obtained from doubling equations and the doubling process was repeated until the results for thick atmospheres were obtained. The number of Gauss divisions in the integrations and the number of terms in the cosine expansions were varied to check the numerical accuracy; this procedure indicated that at all angles the results differed from the exact solution by less than 1%. The results were integrated over the illuminated part of Venus at the phase angle  $59^\circ$  which corresponds to the phase angle at which the observations of Bottema *et al.* were made and approximately to the phase angle ( $53^\circ$ ) of Kuiper's (1962) observations. The "reflectivity" shown in Figs. 3–5 was obtained as the ratio of the calculated reflectivity to the reflectivity of a perfect Lambert sphere at the same phase angle. The fact that the optical thickness of a given cloud would vary with wavelength was neglected; however, for the cloud models considered here the variation in opacity is significant only for wavelengths  $\gtrsim 2.25\ \mu$  and in much of that region the reflectivity is nearly independent of the optical thickness (Figs. 3–5).

#### 4. Discussion

Figs. 3–5 illustrate the dependence of the absorption features on particle size and on the cloud optical thickness. For particles still smaller than those shown the reflectivity in the  $3.0$ – $3.4\ \mu$  region continues to increase rapidly. Thus, if the upper limits on the reflectivity in

that region suggested by the observations of Bottema *et al.* (see Section 2) are accepted, then, for the clouds of Venus to be ice, they must be composed primarily of particles  $\gtrsim 1 \mu$  in radius. (The cloud particles could, of course, be ice particles submicron in radius if we were willing to invoke an additional absorber for  $\lambda \sim 3.0\text{--}3.4 \mu$ .)

It is more difficult to establish an upper limit for the particle size since the  $1.5$  and  $2.0 \mu$  features depend strongly on the cloud optical thickness. However, since the absorption features become still stronger for particles larger than those represented in Fig. 5, it is apparent that for the cloud thickness preferred by Sagan and Pollack ( $\tau \sim 30$ ), the cloud particles could not be as large as they originally derived ( $7.5 \mu \leq \bar{r} \leq 10 \mu$ ). In fact, for ice clouds of that thickness, it does not appear that particles of any size could be compatible with the observations of both Kuiper and Bottema *et al.* Moreover, if the maximum depression in the continuum at  $2.0 \mu$  allowed by Kuiper's observations is 1%, then potential ice clouds would have to be so thin that they could not be regarded as the primary scatterers of visual and infrared radiation. However, if it is assumed that Kuiper's observations permit reflectivity absorption features of  $\sim 20\%$ , then clouds of optical thickness  $\lesssim 10$  and particle radii  $1 \mu \lesssim \bar{r} \lesssim 4 \mu$  are acceptable.

It is clear that ice clouds of thickness  $\tau \sim 5\text{--}10$  would have to be regarded as the major scatterers of visual and near infrared radiation. The visual spherical albedo for clouds of optical thickness 5 and 10 would be  $\sim 40\%$

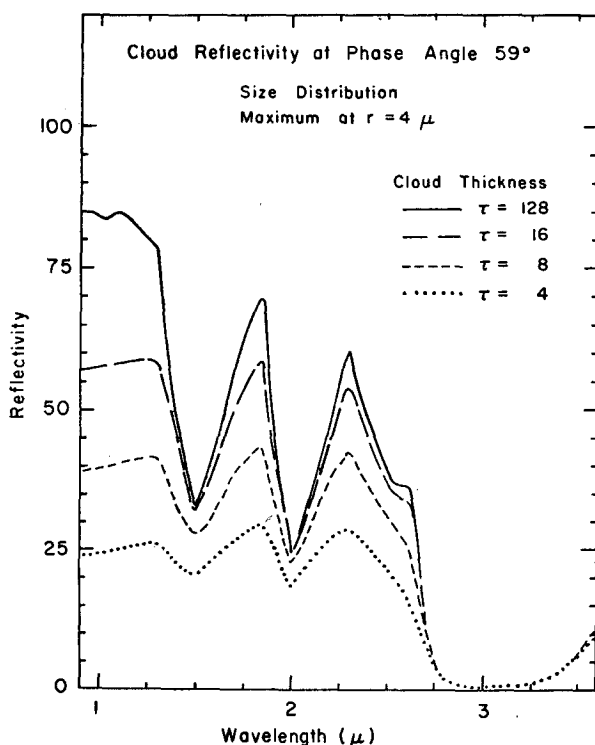


FIG. 5. Same as Fig. 3 except the size distribution has its maximum at  $4 \mu$ .

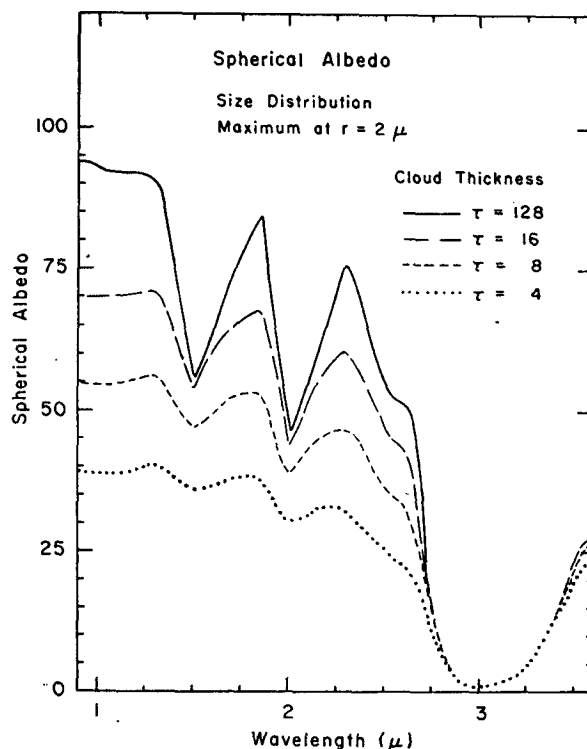


FIG. 6. Spherical albedo of ice clouds in the near infrared. The calculations are for the "cloud" model size distribution of spherical ice particles with the maximum of the distribution at radius  $2 \mu$ .

and 55%, respectively. The spherical albedo in the near infrared is shown in Fig. 6 for the particle size distribution peaking at  $r = 2 \mu$ . It is interesting, although not too significant, that the spherical albedo for Venus at  $2.3 \mu$  is  $\sim 40\%$  (Sinton, 1963) in agreement with an ice cloud of thickness  $\tau \sim 5$ , but the observed value is uncertain. The spherical albedo of Venus in the visual is  $\sim 70\text{--}80\%$  and hence, for the clouds suggested above, the reflectivity in that wavelength region would have to receive a significant contribution from ground reflection, dust particle scattering, or Rayleigh scattering from below the ice clouds, but such possibilities are not unexpected for visual light.

It is important, however, to question the physical plausibility of having relatively thin planetwide ice clouds. Certainly such clouds could not be expected to be of uniform thickness even if the circulation pattern on Venus is unicellular. There would probably be some areas of the planet with no ice clouds at all, but with the resolution obtainable from earth it is doubtful that these could be observed, especially since the atmosphere below the cloud tops almost certainly contains fine dust particles as a result of the dry surface conditions. In fact, it would be difficult to fit any model with a single type of scattering particle, either ice or dust, to all of the observations. The reflectivity of the planet is relatively constant from  $2000\text{--}3000 \text{ \AA}$  in the ultraviolet

(Jenkins and Morton<sup>2</sup>) with an albedo about half of that in the visual. Deep clouds of ice or water would have practically the same albedo in the ultraviolet as in the visual and according to Pollack (private communication) the albedo of dust clouds, which is low at 3000 Å, would continue to decrease toward 2000 Å if the increased ultraviolet absorption is due to  $\text{Fe}_3^+$  as it is for most dusts on earth. The flat reflectivity from 2000–3000 Å would be understandable, however, if thin or broken ice clouds provide about half of the visual albedo as would be the case with clouds of average optical thickness  $\tau \sim 5$ –10.

A recent observation which is of special significance to this paper is that of the water vapor mixing ratio below the clouds which was measured by Venera 4 (Avduevsky *et al.*, 1968) as  $>0.1\%$ . If that result is correct, then it is probable that there are ice clouds covering at least part of the planet. Although the Venera 4 result apparently contradicts several water vapor line measurements, it is just conceivable that the spectroscopic results are also compatible with ice clouds. The polarization measurements contain much information on the cloud particles but the results of those measurements are ambiguous; Lyot (1929) deduced a refractive index  $\sim 1.33$  and a particle radius  $\sim 1.25 \mu$  but Coffeen (1968) infers a refractive index between 1.4 and 1.7. Moreover, since the polarization is primarily due to singly scattered photons, it is possible that these measurements refer mainly to a thin haze layer above the clouds.

We have not mentioned many observations which bear on the cloud particle composition, but none of those observations unambiguously rules out the possible existence of ice clouds. We conclude from the near infrared reflectivity spectra that the clouds of Venus are not optically thick ice clouds; however, if depressions in the continuum  $\sim 20\%$  are accepted, then thin ice clouds ( $\tau \sim 5$ –10) with particle radii  $1 \mu \lesssim \bar{r} \lesssim 4 \mu$  are compatible with the infrared observations.

*Acknowledgments.* We would like to thank Drs. A. Arking, R. Jastrow, G. P. Kuiper, W. Plummer, J. Pollack and J. Potter for helpful comments and dis-

cussions. We would also like to thank Dr. Jastrow, the director of the Institute for Space Studies, for his hospitality. During the course of this research J. E. H. held a National Research Council Postdoctoral Research Associateship supported by the National Aeronautics and Space Administration and H. C. was supported by grant NsG 399-016-013 through the Department of Meteorology and Oceanography, New York University.

## REFERENCES

- Avduevsky, V. S., M. Ya. Marov, and M. K. Rozhdestvensky, 1968: Model of the atmosphere of the planet Venus based on results of measurements made by the Soviet automatic interplanetary station Venera 4. *J. Atmos. Sci.*, **25**, 537–545.
- Bottema, M., W. Plummer, J. Strong and R. Zander, 1964: Composition of the clouds of Venus. *Astrophys. J.*, **140**, 1640–1641.
- , —, — and —, 1965: The composition of the Venus clouds and implications for model atmospheres. *J. Geophys. Res.*, **70**, 4401–4402.
- Coffeen, D. L., 1968: Optical polarization of Venus. *J. Atmos. Sci.*, **25**, p. 643.
- Deirmendjian, D., 1964: Scattering and polarization properties of water clouds and hazes in the visible and infrared. *Appl. Opt.*, **3**, 187–196.
- Hansen, J. E., 1968: Radiative transfer by doubling very thin layers. (To be published).
- , and H. Cheyney, 1968: Comparison of theoretical near infrared reflectivities of ice clouds to laboratory observations. (To be published).
- Irvine, W. M., and J. B. Pollack, 1968: Infrared optical properties of water and ice spheres. *Icarus*, **8**, 324–360.
- Kuiper, G. P., 1962: Photometry of the infrared spectrum of Venus, 1–2.5 microns. *Commun. Lunar Planet. Lab.*, **1**, 83–117.
- Lyot, B., 1929: Recherches sur la polarisation de la lumière des planètes et de quelques substances terrestres. *Ann. Obs. Paris (Meudon)*, **8**, 161 pp.
- Pollack, J. B., and C. Sagan, 1968: The case for ice clouds on Venus. *J. Geophys. Res.*, **73** (in press).
- Rea, D. G., and B. T. O'Leary, 1968: On the composition of the Venus clouds. *J. Geophys. Res.*, **73**, 665–675.
- Sagan, C., and J. B. Pollack, 1967: Anisotropic nonconservative scattering and the clouds of Venus. *J. Geophys. Res.*, **72**, 469–477.
- Sinton, W. M., 1963: Infrared observations of Venus. *Mem. Soc. Roy. Sci., Leige*, **7**, 300–310.
- Strong, J. *et al.*, 1966: Infrared balloon astronomy. Air Force Cambridge Res. Labs., Rept. 66-616, 302 pp. (Defense Document Center, AD 643 567, \$3.00).
- van de Hulst, H. C., 1963: A new look at multiple scattering. Institute for Space Studies, NASA, New York, Rept., 81 pp.

<sup>2</sup> Jenkins, E. B., and D. C. Morton, 1968: Paper presented at the Second Arizona Conference on Planetary Atmospheres, Tucson, 11–13 March.